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ELECTRONIC PHASE SHIFTER WITH ENHANCED PHASE SHIFT PERFORMANCE

BACKGROUND OF THE INVENTION

An emerging class of consumer electronic devices are wireless data access units that permit, for example, a portable laptop computer to be connected to a data network using radio waves. Ideally, such access devices take the form factor of a small handheld unit, much in the nature of the well-known cellular mobile telephone handsets. Because the users of such systems demand the highest data rate possible, given a specific available bandwidth for providing the service, these units are increasingly being designed to take advantage of sophisticated antenna techniques.

These techniques involve typically the use of antenna arrays that permit the radio link between the access unit and a centralized network base station to be made over a directional or diverse connection. The directivity provided by an antenna array reduces interference generated by a given radio connection with connections made to other access units operating within the same region, or cell, serviced by a particular base station. In order to accomplish the required directivity of the antenna array a number of components may be used to create the antenna beam. This may include switches, delay circuits, or phase shifters; the phase shifters provide the maximum control over the direction and shape of the resulting beam.

It becomes desirable therefore to provide for phase shifters that are as

efficient, low-loss, and provide as wide a phase shift range as possible. Ideally, such phase shifter circuits are constructed using planar circuit techniques so that they may be as small and as inexpensive as possible. These requirements are critical if such phase shifters are to be effectively and economically deployed in portable access unit equipment.

At operating frequencies in the Very High Frequency (VHF) and higher frequency bands, one such circuit design makes use of a four port directional coupler. This design uses one or more varactors coupled to quadrature ports of the directional coupler. If the directional coupler is a half power, i.e., three decibel (dB) coupler, the reflections from the quadrature port(s) are equally recombined at the fourth output port. The signals combined at the output port will have a phase that is quasi-proportional to the impedance phase angle of the varactor(s). Thus, the amount of phase shift provided is a monotonic function that varies as the inverse of the line impedance.

SUMMARY OF THE INVENTION

The present invention is an improvement to a class of varactor based phase shifters that provides an increase in phase shift range and a reduction in the circuit requirements of the varactor components.

Briefly, the invention makes use of the property that a lower line impedance will provide greater phase shift, relying a unique technique to realize the lower line impedance. The technique used to achieve lower impedance is to embed a quarter-wave impedance transformer into the directional coupler, without adding extra signal path line lengths.

For example, if the input to output impedance is 50 ohms, which is the standard instrumentation line impedance, the impedance transformer implements a 50 ohm to 20 ohm transformation. In this embodiment, the impedance transformer may take the form of a pair of circuit traces. The first circuit trace runs from the input port to a quadrature port, and has a width that presents a 22 ohm impedance and a length that approximates

one-quarter wavelength at the operating frequency. The 22 ohms is determined from the equation

$$\sqrt{Z_{O1}Z_{O2}}\ /F_{QC}$$

where Z_{01} is the input-output port impedance (50 ohms), Z_{02} is the quadrature port impedance (20 ohms), and F_{QC} is a quadrature hybrid coupler factor. In the case of a branch line coupler, F_{QC} is equal to $\sqrt{2}$.

The second circuit trace, running from the second quadrature port to the output port, is similarly formed from a conductive path that presents the 22 ohm transform impendence, and a length also of the desired one-quarter wavelength.

The quadrature ports each have attached thereto a varactor diode. The varactor diodes are biased by an input control voltage applied to the quadrature ports.

Coupling between the input/output port and between the quadrature ports may be provided by a circuit trace a quarter wave long connected between the respective ports. In the case of the input to output port, the circuit trace carries the characteristic desired 50 ohm impedance. Between the quadrature ports, the circuit trace provides the 20 ohm impedance desired across the quadrature ports.

In an alternative arrangement, quarter wave long face-coupled lines may provide the desired coupling between the input and output ports as well as between the coupling between quadrature ports.

The invention improves the available phase shift range by a factor of approximately 70% when compared to a standard 50 ohm to 50 ohm design, with comparable loading such as a single varactor coupled to each quadrature port.

Although the basic application of the invention is described in connection with the use of phase shifters, the technique can be used in a broader range of devices as well.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a portable access unit, such as may be used to provide wireless internet connectivity, with the unit having one more phase shifters implemented according to the invention.

Fig. 2 is a circuit diagram for a varactor based quadrature port phase shifter implemented according to the invention.

Fig. 3 is a circuit layout for one implementation of the phase shifter showing the impedance transformers coupled between the input and quadrature port and quadrature port and output.

Fig. 4A and 4B, are respectively, Smith chart diagrams for respectively a prior art phase shifter and the present invention, showing the increase in available phase shift range.

Fig. 5 is a circuit layout for an alternate embodiment of the invention using coupled lines.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A description of preferred embodiments of the invention follows.

Turning attention first to Fig. 1, there is shown a block diagram of one particular application of a phase shifter having improved phase shift range according to the invention. This device is a subscriber access unit 10 for a wireless communication system, and is seen to include an antenna array 12, antenna Radio Frequency (RF) sub-assembly 20, and an electronics sub-assembly 30. The subscriber access unit 10 may be used to provide wireless data connectivity such as between the user of a laptop computer 60 and data networks such as the Internet. A wireless base station unit (not shown in Fig. 1) provides network connectivity through internetwork switches or routers. In the typical scenario, a number of subscriber access units 10 are located within the area surrounding a base station and are serviced by the common base station. However, other arrangements are possible.

Before, turning attention to the phase shifter 25 in particular, it will be instructive to understand how the subscriber access unit 10 operates in general. Wireless signals arriving from the base station are first received at the antenna array 12 which consists of a number of antenna elements 14-1, 14-2, ..., 14-N. The signals arriving at each antenna element are fed to an RF subassembly 20, including, for example, a phase shifter 25, delay 24, and/or switch 23. There is an associated phase shifter 25, delay 24, and/or switch 23 associated with each antenna element 14.

The signals are then fed through a combiner divider network 22 which typically adds the vector voltages in each signal chain providing the summed signal to the electronics sub-assembly 30.

In the transmit direction, radio frequency signals provided by the electronic sub-assembly 30 are fed to the combiner divider network 22. The signals to be transmitted follow through the signal chain, including the switch 23, delay 24, and/or phase shifter 25 to a respective one of the antenna elements 14, and from there are transmitted back towards the base station.

In the receive direction, the electronics sub-assembly 30 receives the radio signal at the duplexer/filter 32 which provides the received signals to the receiver 35. The radio receiver 35 provides a demodulated signal to a decoder circuit 37 that removes the modulation coding. For example, such decoder may operate to remove Code Division Multiple Access (CDMA) type encoding which may involve the use of pseudorandom codes and/or Walsh codes to separate the various signals intended for particular subscriber units, in a manner which is known in the art. The decoded signal is then fed to a data buffering circuit 40 which then feeds the decoded signal to a data interface circuit 50. The interface circuit 50 may then provide the data signals to a typical computer interface such as may be provided by a Universal Serial Bus (USB), PCMCIA type interface, serial interface or other well-known computer interface that is compatible with the laptop computer 60. A controller 46 may receive and/or transmit messages from the data interface to and from a message interface circuit 44 to control the operation of the decoder 37, encoder 36, the tuning of the transmitter 34 and receiver 35. This may also provide the control signals 62 associated with controlling the state of the switches 23, delays 24, and/or phase shifters 25. For example, a first set of control signals 62-3 may control the phase shifter states such that each individual phase shifter 25 imparts a particular desired phase shift to one of the signals received from or transmitted by the respective antenna element 14. This permits the steering of the entire antenna array 12 to a particular desired direction, thereby increasing the overall available data rate that may be accomplished with the equipment. For example, the access unit 10 may receive a control message from the base station commanded to steer its array to a particular direction and/or circuits associated with the receiver 35 and/or decoder 37 may provide signal strength indication to the controller 46. The controller 46 in turn, periodically sets the values for the phase shifter 25.

As mentioned above, of particular interest to the present invention is the construction of the phase shifter 25.

Turning now to Fig. 2, there is shown a more detailed circuit diagram of the preferred embodiment of the phase shifter 25 as a four port device. In particular, the phase shifter 25 includes an input port (IN) 100, an output port (OUT) 200, a first quadrature port (Q1) 150, and a second quadrature port (Q2) 160. The input port 100 and output port 200 have an associated characteristic impedance Z_{O1}. Similarly, the quadrature ports 150 and 160 have associated with them a characteristic impedance Z_{O2}. Coupled between the input port 100 and quadrature port 150 is an impedance transformer 120. The impedance transformer provides for a transformation from the characteristic impedance Z_{O1} between the input port 100 and the output port 200 to the characteristic impedance Z_{O2} between the quadrature ports 150 and 160. As will be understood shortly, in connection with the description of Fig. 3, the impedance transformer 120 is implemented using a strip of transmission line of the appropriate length. Similarly, an impedance transformer 130 is connected between the second quadrature port 160 and the output port 200. It is these impedance transformers 120 and 130 that provide for increased phase range in connection with the novel aspects of the present invention.

A varactor diode 180 is connected between the first quadrature port 150 and a ground reference potential; similarly, a second varactor diode 190 is connected between the second quadrature port 160 and the ground reference as well. A bias input voltage representing the signal 62-3 which was provided in the description of Fig. 1 to control the phase shift imported by the phase shifter 25 is applied to the quadrature ports 150 and 160. An RF blocking inductor 195 may be typically disposed in the bias input. In addition, blocking capacitors 112 and 114 may be applied to the input port 100 and output port 200 to prevent the introduction of direct current signals beyond the phase shifter circuit 25. In the preferred embodiment, the four port coupler arrangement is a one-quarter wave device having a line length of $\lambda/4$. One implementation of such a coupler is a so-called branch line coupler, as shown in Fig. 3. Fig. 3 is a circuit layout diagram illustrating a planar implementation of the invention. Particular circuit

elements, including the input blocking capacitors 112 and 114, varactor diodes 180 and 190, and RF blocking inductor 195 are implemented using known planar circuit techniques. In this implementation, the impedance transformer circuits 120 and 130 are provided by sections of transmission line 121 and 131 having a length equal to one-quarter wavelength of the desired operating frequency. The distance $\lambda/4$ associated with the impedance transformer 120 and 130 is as measured from a center line of the center line C of each end of the circuit structure.

The width, w_1, associated with the impedance transformers 120 and 130 is selected to provide the appropriate transformation from the characteristic input impedance Z_{O1} across the input port 100 and output port 200 to the characteristic impedance Z_{O2} associated across the quadrature ports 150 and 160. The formula is

$$Z_{OT} = \sqrt{Z_{O1} Z_{O2}} \; / F_{QC}$$

where F_{QC} is a quadrature hybrid factor value that depends upon the hybrid coupler design. In the case of a branch line coupler, the F_{QC} factor is known to the practitioners to be $\sqrt{2}$.

In this embodiment, the impedance transformers 120 and 130 have a width, w_1, that approximately provides a 22 ohm impedance to current flow.

Coupling between the input port 100 and output port 200 is provided by a straight branch line 155, in this embodiment. The branch line 155 has a width, w_0, that provides the desired characteristic impedance; here this impedance is 50 ohms. Also in this embodiment, another one quarter wavelength branch line 158 provides coupling between the quadrature ports 150 and 160. This branch line 158 has a width, W_2, that provides the desired characteristic impedance between the quadrature ports of 20 ohms. The branch lines 155 and 158 may be straight or follow a serpentine path as is illustrated. The serpentine path permits the overall dimension of the phase shifter 25 to

be less than would otherwise be required; for in the preferred embodiment, the overall length of each of the branch lines 155 and 158 is $\lambda/4$.

By changing the voltage applied to the bias terminal, the reactance of the varactors 180 and 190 changes. This provides a change in the phase shift imparted by the pair of varactors 180 and 190, in turn effecting a phase change at the quadrature ports 150 and 160. This results in an insertion phase shift being evident in the signal going from the input port to the output port.

A dramatic increase in the amount of available phase shift range is available with the introduction of the impedance transformers 120 and 130. This difference is illustrated by the Smith charts in Figs. 4A and 4B. Fig. 4A represents a Smith chart for a prior art phase shifter in which the characteristic impedance between the input and output ports and across the quadrature ports are each set at 50 ohms. Such an implementation provides a phase shift range as illustrated, for example, of approximately 80°, going from the inductive zone to the capacitive zone. The prior art circuit implementation made the assumption that matching the characteristic impedance at both ends of the four port device provides for the best performance. However, with the present invention, it is clear that by dropping the characteristic impedance across the quadrature ports to 20 ohms, as shown in Fig. 4B, the overall available phase shift range has been marketedly increased such as, for example, to a range of approximately 200°.

The narrow line widths on either side of each varactor are designed in to provide added inductance to the varactors, so that when the varactors are under bias, they can exhibit both inductive and capacitive properties. This allows the phase shift to vary over a broader range of degrees in both the capacitive and inductive zones about the 180° point, as shown in Fig. 4B.

Fig. 5 illustrates an alternative arrangement for the invention making use of a so-called cross line face-coupled coupler. In this embodiment, coupling between the input and output ports is provided by a pair of transmission lines in a cross coupled orientation, as shown at 225 between the 50 ohm input port 100 and 50 ohm output port

200. Similarly, a pair of cross coupled lines may be provided to implement the coupling between the 20 ohm quadrature ports 150 and 160, as illustrated at 258. Cross-coupling is implemented by forming one set of the circuit traces and components on a first layer of a printed circuit board, as shown with the solid lines, and a second set of traces and components on another layer of the printed circuit board, as shown with the dashed lines. As is know to those of skill in the art, each pair of cross-coupled lines provides a 6 dB directional coupler. Two pairs of these coupled lines in tandem make up a 3 dB coupler, or a hybrid, which has the same properties as the branch line coupler.

The transformers 120 and 130 are one quarter wavelength long. The characteristic impedance of the transformers are 32 ohms, which is different from the previous branch line example. The difference is due to the fact that the quadrature hybrid factor, F_{QC}, in the case of the crossed line coupler is one (1), instead of $\sqrt{2}$.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.